

Search for $K_S^0 K_S^0$ in J/ψ and $\psi(2S)$ decays

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The CP violating processes $J/\psi \rightarrow K_S^0 K_S^0$ and $\psi(2S) \rightarrow K_S^0 K_S^0$ are searched for using samples of 58 million J/ψ and 14 million $\psi(2S)$ events collected with the Beijing Spectrometer at the Beijing Electron Positron Collider.

1. Introduction

The decay of $J^{PC} = 1^{--}$ charmonium states, like J/ψ and $\psi(2S)$, to $K_S^0 K_S^0$ is a CP violating process. However, since CP violations in both the $K^0 \bar{K}^0$ and $B^0 \bar{B}^0$ systems have been well established [1], it is of interest to search for them in other possible processes.

Furthermore, it has been shown [2] that the $K_S^0 K_S^0$ system can be used to test the Einstein-Podolsky-Rosen (EPR) paradox versus quantum theory. The space-like, separated coherent quantum system may yield some $J/\psi \rightarrow K_S^0 K_S^0$ decays if EPR's locality is correct while quantum theory forbids this process.

MARK-III searched for decays of $J/\psi \rightarrow K_S^0 K_S^0$ with 2.7 million J/ψ events [3]. No signal was observed, and the upper limit on the decay branching ratio was determined to be $\mathcal{B}(J/\psi \rightarrow K_S^0 K_S^0) < 5.2 \times 10^{-6}$ at the 90% confidence level (C. L.). The same search for $\psi(2S)$ decays has not been performed before.

In this Letter, we report on a search for $J/\psi \rightarrow K_S^0 K_S^0$ using a sample with 20 times more statistics than before, and on the first search for $\psi(2S) \rightarrow K_S^0 K_S^0$. The data samples used for the analyses are taken with the Beijing Spectrometer (BESII) detector at the Beijing Spectrometer (BEPC) storage ring at a center-of-mass energies corresponding to $M_{J/\psi}$ and $M_{\psi(2S)}$. The data samples contain $(57.7 \pm 2.7) \times 10^6$ J/ψ events and $(14 \pm 0.7) \times 10^6$ $\psi(2S)$ events, as determined from inclusive hadronic decays [4,5].

BES is a conventional solenoidal magnet detector that is described in detail in Ref. [6]; BESII is the upgraded version of the detector [7]. A 12-layer vertex chamber (VC) surrounding the beam pipe provides trigger information. A forty-layer main drift chamber (MDC), located radially outside the VC, provides trajectory and energy loss (dE/dx) information for charged tracks over 85% of the total solid angle. The momentum resolution is $\sigma_p/p = 0.017\sqrt{1+p^2}$ (p in GeV/c), and the dE/dx resolution for hadron tracks is $\sim 8\%$. An array of 48 scintillation counters surrounding the MDC measures the time-of-flight (TOF) of charged tracks with a resolution of ~ 200 ps for hadrons. Radially outside the TOF system is a 12

radiation length, lead-gas barrel shower counter (BSC). This measures the energies of electrons and photons over $\sim 80\%$ of the total solid angle with an energy resolution of $\sigma_E/E = 22\%/\sqrt{E}$ (E in GeV). Outside of the solenoidal coil, which provides a 0.4 Tesla magnetic field over the tracking volume, is an iron flux return that is instrumented with three double layers of counters that identify muons of momentum greater than 0.5 GeV/c.

2. Monte Carlo

A Monte Carlo (MC) simulation is used for the determination of mass resolutions and detection efficiencies. For the signal channels, $J/\psi \rightarrow K_S^0 K_S^0$ and $\psi(2S) \rightarrow K_S^0 K_S^0$, the angular distribution of one K_S^0 is generated with the same distribution as for the CP allowed channels $J/\psi \rightarrow K_S^0 K_L^0$ and $\psi(2S) \rightarrow K_S^0 K_L^0$, namely as $\sin^2 \theta$, where θ is the polar angle of the K_S^0 in the laboratory system. Only $K_S^0 \rightarrow \pi^+ \pi^-$ is generated, and the K_S^0 is allowed to decay in the detector according to its lifetime. The simulation of the detector response is done using a Geant3 based program with detailed consideration of the detector performance (such as dead electronic channels). Reasonable agreement between data and Monte Carlo simulation has been observed in various channels tested, including $e^+e^- \rightarrow (\gamma)e^+e^-$, $e^+e^- \rightarrow (\gamma)\mu^+\mu^-$, $J/\psi \rightarrow p\bar{p}$ and $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$). For this study, 10,000 events for each signal channel are produced.

3. Event selection

For the decay channels of interest, the candidate events are required to satisfy the following selection criteria:

1. The number of charged tracks is required to be four with net charge zero. Each track should satisfy $|\cos \theta| < 0.8$, where θ is the polar angle in the MDC, and should have a good helix fit so that the error matrix of the track fitting is available for secondary vertex finding.
2. The tracks are assumed to be either π^+ or π^- . The higher momentum positive track

and the lower momentum negative track are assumed to come from one of the K_S^0 decays, and the remaining two tracks are assumed to come from the other K_S^0 decay. The intersection of the track-pairs near the interaction point are determined and are regarded as the K_S^0 vertices.

- Each K_S^0 candidate is required to have a decay length in the transverse plane (L_{xy}) greater than 3 mm and an invariant mass within twice the mass resolution as estimated from Monte Carlo simulations (the mass resolution in J/ψ decays is $7.1 \text{ MeV}/c^2$ and in $\psi(2S)$ decays $7.9 \text{ MeV}/c^2$).

For $\psi(2S)$ decays, backgrounds from $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$ with J/ψ decaying into two charged tracks are removed by further requiring the mass recoiling against the lower momentum positive and negative tracks, m_{rec} , to be less than $3.0 \text{ GeV}/c^2$. The comparison of the recoil mass distributions of signal and background events from Monte Carlo simulation is shown in Figure 1. It can be seen that this requirement is very efficient in removing background, and the loss of efficiency is small ($\sim 4\%$).

Another possible background is from $\psi(2S) \rightarrow \gamma\chi_{cJ}$ ($J = 0, 2$) with $\chi_{cJ} \rightarrow K_S^0 K_S^0$. Figure 2 shows $K_S^0 K_S^0$ missing momentum distributions for the signal and background channels, all simulated by Monte Carlo. We make an additional requirement $p_{miss} < 0.1 \text{ GeV}/c$ for $\psi(2S)$ selection. This removes 94% of χ_{c2} background and almost all the χ_{c0} background, while the efficiency for $\psi(2S) \rightarrow K_S^0 K_S^0$ is about 92% according to Monte Carlo simulation. For J/ψ decays, since $\eta_c \rightarrow K_S^0 K_S^0$ is forbidden by parity conservation, no requirement is applied.

The momenta of the two K_S^0 tracks for events passing the above selection are plotted in Figures 3 and 4, for J/ψ and $\psi(2S)$ decays, respectively, together with the regions predicted for signal events by the Monte Carlo simulation. The two circles correspond to

$$\sqrt{(p_{K_S^0}^a - p_0)^2 + (p_{K_S^0}^b - p_0)^2} < n\sigma,$$

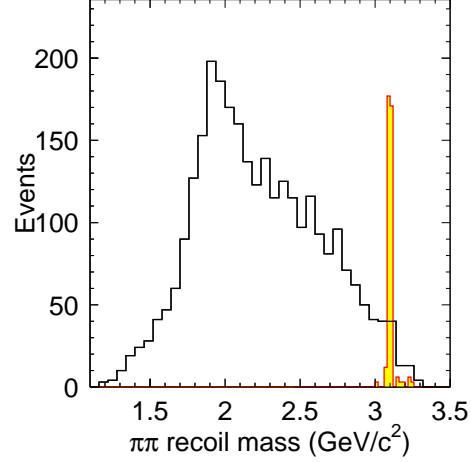


Figure 1. Recoil mass distributions of Monte Carlo simulated $\psi(2S) \rightarrow K_S^0 K_S^0$ (blank histogram) and $\psi(2S) \rightarrow \pi^+\pi^-J/\psi$, $J/\psi \rightarrow \ell^+\ell^-$ ($\ell = e, \mu$) (shaded histogram). The histograms are not normalized. The requirement $m_{rec} < 3.0 \text{ GeV}/c^2$ is applied in the selection of $\psi(2S)$ events.

where $p_{K_S^0}^a$ and $p_{K_S^0}^b$ are the momenta of the two K_S^0 candidates in the event; σ is the K_S^0 momentum resolution, which is $28 \text{ MeV}/c$ in J/ψ decays and $34 \text{ MeV}/c$ in $\psi(2S)$ decays, as determined from Monte Carlo simulations; and p_0 is the expected K_S^0 momentum in J/ψ (1.466 GeV) or $\psi(2S)$ (1.775 GeV) two-body decays. The inner circles correspond to $n = 1$, and the outer circles are for $n = 2$. It can be seen that there are no candidate events in either J/ψ or $\psi(2S)$ decays within the one σ circle, and there is only one candidate in each case lying between the one and two σ circles. Using the 2σ circle for our event selection, one event is obtained each for $J/\psi \rightarrow K_S^0 K_S^0$ and for $\psi(2S) \rightarrow K_S^0 K_S^0$. The corresponding efficiencies, ε_{MC} , are 20.74% and 19.18% for J/ψ and $\psi(2S)$ decays, respectively, as estimated from Monte Carlo samples.

The backgrounds remaining in both J/ψ and $\psi(2S)$ decays after the K_S^0 requirement are studied with Monte Carlo simulations. The main

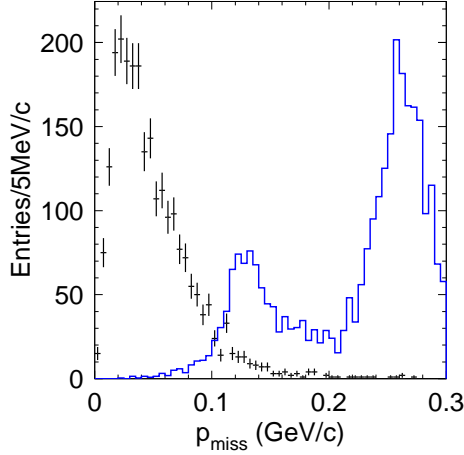


Figure 2. Missing momentum distributions of Monte Carlo simulated $\psi(2S) \rightarrow K_S^0 K_S^0$ (error bars) and $\psi(2S) \rightarrow \gamma \chi_{cJ}, \chi_{cJ} \rightarrow K_S^0 K_S^0$ ($J = 0, 2$) (histogram). The histograms are not normalized. An additional requirement of $p_{\text{miss}} < 0.1$ GeV/c is applied to remove the χ_{cJ} background.

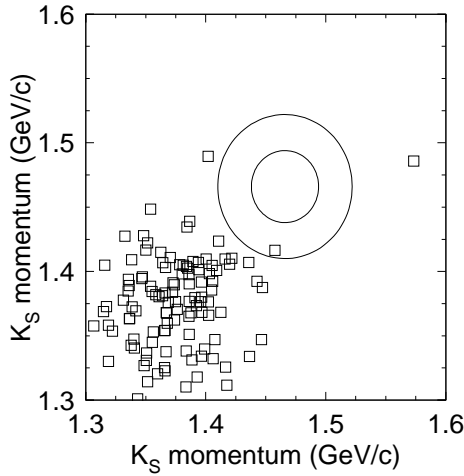


Figure 3. Momentum of one K_S^0 versus the other for the selected J/ψ decay candidates (open squares). The circles correspond to one and two σ regions of Monte Carlo $J/\psi \rightarrow K_S^0 K_S^0$ events.

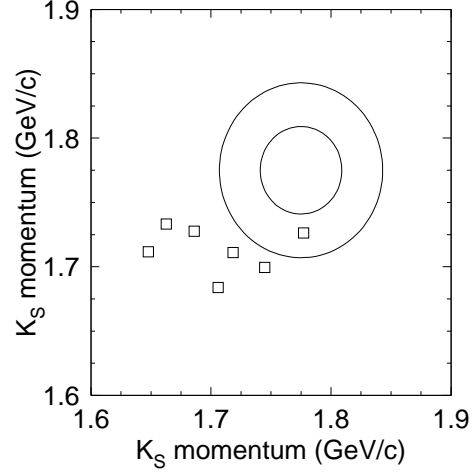


Figure 4. Momentum of one K_S^0 versus the other for the selected $\psi(2S)$ decay candidates (open squares). The circles correspond to one and two σ regions of Monte Carlo $\psi(2S) \rightarrow K_S^0 K_S^0$ events.

background channel in J/ψ decays is from $J/\psi \rightarrow \bar{K}^*(892)^0 K^0 + c.c.$ is estimated to be 1.0 ± 0.4 events, which is obtained using a Monte Carlo sample six times as large as the J/ψ sample. The main background channels in $\psi(2S)$ decays are $\psi(2S) \rightarrow \gamma \chi_{c2}, \chi_{c2} \rightarrow K_S^0 K_S^0$ and $\psi(2S) \rightarrow \bar{K}^*(892)^0 K^0 + c.c.$. A Monte Carlo simulation estimates the total background to be 0.67 ± 0.25 events, with about 80% due to $\chi_{c2} \rightarrow K_S^0 K_S^0$. The errors on the estimated backgrounds are from the uncertainties of the branching ratios used and the limited statistics of the Monte Carlo samples.

The two candidate events are investigated further, and it is found that the $J/\psi \rightarrow K_S^0 K_S^0$ candidate is most likely a $J/\psi \rightarrow \bar{K}^*(892)^0 K^0 + c.c.$, with $K^{*0} \rightarrow K^- \pi^+$ misidentified as $K_S^0 \rightarrow \pi^+ \pi^-$ because no particle identification is used in the event selection, while the $\psi(2S) \rightarrow K_S^0 K_S^0$ candidate looks like a $\psi(2S) \rightarrow \gamma \chi_{c2}, \chi_{c2} \rightarrow K_S^0 K_S^0$ event with an isolated photon with BSC energy of 126 MeV.

4. Trigger efficiency

Due to the long decay length of the high momentum K_S^0 and the requirement of hits in the VC, the trigger efficiency of $K_S^0 K_S^0$ events is lower than for normal hadronic events. Since the trigger system is not included in the Monte Carlo simulation, the trigger efficiency is measured with data by comparing events within and beyond the outer radius of the VC using $J/\psi(\psi(2S)) \rightarrow K_S^0 K_L^0$ events, which yields trigger efficiencies of $(86.7 \pm 0.9)\%$ and $(81.3 \pm 1.9)\%$ for a single K_S^0 in J/ψ and $\psi(2S)$ decays, respectively. For $K_S^0 K_S^0$ events, the trigger efficiency, ε_{trig} , is calculated to be $(98.2 \pm 0.2)\%$ in J/ψ decays and $(96.5 \pm 0.7)\%$ in $\psi(2S)$ decays.

5. Secondary Vertex Finding

The secondary vertex finding algorithm is checked using $J/\psi \rightarrow K^*(892)\bar{K} + c.c.$ events. It is found that the Monte Carlo simulates data fairly well, and extrapolating the difference between data and Monte Carlo simulation to the K_S^0 momentum range under study and correcting by the polar angle dependence of the efficiency, correction factors of $(96.4 \pm 3.1)\%$ and $(98.1 \pm 4.0)\%$ are obtained for a single K_S^0 in J/ψ and $\psi(2S)$ decays, respectively. For $K_S^0 K_S^0$ decays, the correction factors and errors to the Monte Carlo efficiencies, ε_{2nd} , for $J/\psi \rightarrow K_S^0 K_S^0$ and $\psi(2S) \rightarrow K_S^0 K_S^0$ are $(92.9 \pm 4.5)\%$ and $(96.2 \pm 5.8)\%$, respectively.

6. Systematic error

The total systematic error on the branching ratio measurement comes from all sources listed in Table. 1. The simulation of the tracking efficiency agrees with data within 1-2% for each charged track as measured using channels like $J/\psi \rightarrow \Lambda\bar{\Lambda}$ and $\psi(2S) \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \mu^+\mu^-$, and 8% is taken conservatively as the systematic error for the channel of interest.

The Monte Carlo simulated K_S^0 mass and momentum resolutions agree with those of data within statistical uncertainties, as has been checked with J/ψ and $\psi(2S) \rightarrow K_S^0 K_L^0$ samples [8,9]. The requirement that the K_S^0 mass and momentum be within two standard devia-

Table 1

Summary of the systematic errors.

Source	J/ψ (%)	$\psi(2S)$ (%)
MC statistics	2.1	2.0
Trigger efficiency	0.2	0.7
2 nd vertex	4.8	6.0
MDC tracking	8.0	8.0
Resolutions	5.4	5.6
Number of events	4.7	5.0
$\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)$	0.8	0.8
Sum	12.0	12.7

tions introduces systematic uncertainties at the 5-6% level, dominated by the statistical precisions of the comparisons between data and Monte Carlo simulation.

The systematic errors on the p_{miss} and the recoil mass requirements for the $\psi(2S)$ sample depends on the simulation of the momentum of the charged tracks and are already included either in the tracking or in the systematic error quoted for the K_S^0 mass and momentum resolutions. They are not further considered here.

The systematic errors on the total numbers of J/ψ and $\psi(2S)$ events are taken as 4.7% and 5.0%, respectively, and are measured using inclusive hadronic events with four charged hadrons in the final state [4] for J/ψ and using inclusive hadrons for $\psi(2S)$ [5]. The systematic error on the branching ratio used, $\mathcal{B}(K_S^0 \rightarrow \pi^+\pi^-)$ is obtained from the Particle Data Group [10] directly. Adding all the systematic errors in quadrature, the total systematic errors are 12.0% and 12.7% for J/ψ and $\psi(2S)$ decays, respectively.

7. Results

Since the observed numbers of events agree with the expected background levels for the channels under study, upper limits are conservatively set by not subtracting background and taking the events in MC predicted region as signal. With one observed event, the upper limit on the number of events is 4.74 at the 95% confidence level.

The upper limits on the branching ratios of J/ψ

and $\psi(2S) \rightarrow K_S^0 K_S^0$ are calculated with

$$\mathcal{B}(R \rightarrow K_S^0 K_S^0) < \frac{n_{UL}^{obs} / (\varepsilon_{MC} \cdot \varepsilon_{trig} \cdot \varepsilon_{2nd})}{N_R \cdot \mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)^2},$$

where n_{UL}^{obs} is the upper limit of the number of observed events, and N_R is the total number of resonance R events. Using the numbers listed in Table 2, one obtains the upper limits on the branching ratios at the 95% C. L.:

$$\mathcal{B}(J/\psi \rightarrow K_S^0 K_S^0) < 1.0 \times 10^{-6},$$

$$\mathcal{B}(\psi(2S) \rightarrow K_S^0 K_S^0) < 4.6 \times 10^{-6},$$

where the systematic errors are included by lowering the efficiencies by one standard deviation.

Table 2

Numbers used in the calculations of upper limits and the final results.

R	J/ψ	$\psi(2S)$
n_{UL}^{obs}	1	1
n_{UL}^{obs}	4.74	4.74
ε_{MC} (%)	20.74 ± 0.41	19.18 ± 0.39
ε_{trg} (%)	98.2 ± 0.2	96.5 ± 0.7
ε_{2nd} (%)	92.9 ± 4.5	96.2 ± 5.8
$N_{\psi(2S)} (10^6)$	57.7 ± 2.7	14.0 ± 0.7
$\mathcal{B}(K_S^0 \rightarrow \pi^+ \pi^-)$	0.6860 ± 0.0027	
$\mathcal{B}(R \rightarrow K_S^0 K_S^0) <$	1.0×10^{-6}	4.6×10^{-6}

8. Summary

The CP violating processes $J/\psi \rightarrow K_S^0 K_S^0$ and $\psi(2S) \rightarrow K_S^0 K_S^0$ are searched for using the BESII 58 million J/ψ event and 14 million $\psi(2S)$ event samples. The upper limits on the branching ratios are determined to be $\mathcal{B}(J/\psi \rightarrow K_S^0 K_S^0) < 1.0 \times 10^{-6}$ and $\mathcal{B}(\psi(2S) \rightarrow K_S^0 K_S^0) < 4.6 \times 10^{-6}$ at the 95% C. L. The former is much more stringent than the previous MARK-III measurement [3], and the latter is the first search for this channel in $\psi(2S)$ decays. Current bounds of the production rates still beyond the sensitivity for testing the EPR paradox [2].

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